Iceberg Temperatures

Preliminary Report

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C-CORE

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ABSTRACT

The engineering properties of freshwater ice are largely dependent on its temperature. As virtually nothing is known of the temperature range of icebergs along the coasts of Newfoundland and Labrador a study was undertaken to try to predict the range to be expected in this area and to measure the temperatures of several icebergs to confirm these predictions. While the findings to date are by no means exhaustive, there is a strong suggestion that the bulk temperatures of icebergs in the areas considered may fall in a range of roughly -15^{o} to $-20^{o}C$.

ACKNOWLEDGEMENTS

I wish to acknowledge the assistance of Dr. E. Reimer whose advice and suggestions throughout the preparation of this report were extremely valuable.

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1. INTRODUCTION

The presence of icebergs in the Labrador Sea and North Atlantic has long presented a hazard to shipping. Prior to the introduction of radar they were virtually undetectable in the fog and at night and extreme care had to be exercised to avoid collision. However, since a ship is highly manoeuverable collision can be avoided with reasonably short forewarning and the development and improvement of radar have removed much of the danger of steaming through berg-infested waters.

In recent years, however, there has been a proliferation in these same waters of immobile and semi-mobile structures such as well-heads, underwater cables and semi-submersible drilling platforms. The danger presented to these by icebergs is graver and of a different nature. In the case of drilling platforms, a relatively long lead time is required to allow for orderly removal of the drill stem and capping of the well before the rig can be moved. This can be a very costly operation in terms of time and productivity lost. In some cases the approaching berg can be towed or deflected, but 2 million tons is effectively the maximum size which can be handled in this way and this does not represent a very large iceberg. A larger berg would either have to be avoided or fragmented. The only reported instance (Barnes, 1927) of a berg having been broken up successfully involved the use of thermite, a very hot, slow burning explosive. The explanation for its success was that the ice was fractured by thermal shock induced by the very high temperature in its interior. This could only happen in a cold berg.

In the case of a totally immobile structure such as a gravity platform (Hibernia), a pipeline or a well-head, the structure must be designed to resist an impact if serious and costly damage is to be avoided. In order to design such a structure the mechanical properties of the ice must be known.

The physical and mechanical properties of ice depend to a very great extent on its temperature (e.g. Yakovlev, 1971; Haynes, 1979; Butkovich, 1954; Pounder, 1965). For example, the difference between 0^{o} ice and -15^{o} ice may be a factor of 3 in terms of crushing strength (Butkovich, 1954). Figure 1 shows the effect of temperature on the crushing strength of clear lake ice. Butkovich (1959) in later work on glacier ice near Camp Tuto, Greenland, found crushing strengths at $-5^{o}C$ between 40 and 60 kg/cm^2 while Mellor and Kovacs (1972) report values near 120 kg/cm^2 for ice of density $0.88gm/cm^3$ and $0.91\ gm/cm^3$ below $-20^{o}C$. While compressional (crushing) strength shows greatest dependance on temperature, tensile and shear strengths have also been shown to be temperature dependant to some extent. It follows from this that a knowledge of the range, median and mode of the temperatures of the iceberg population on the Labrador Shelf is of considerable importance to engineers and scientists concerned with potential collisions. This information is unknown at present.

This report is a review of field work and theoretical studies which have been done pertaining to the temperature of icebergs in addition to a description of work done to date by the author and proposed for the near future.

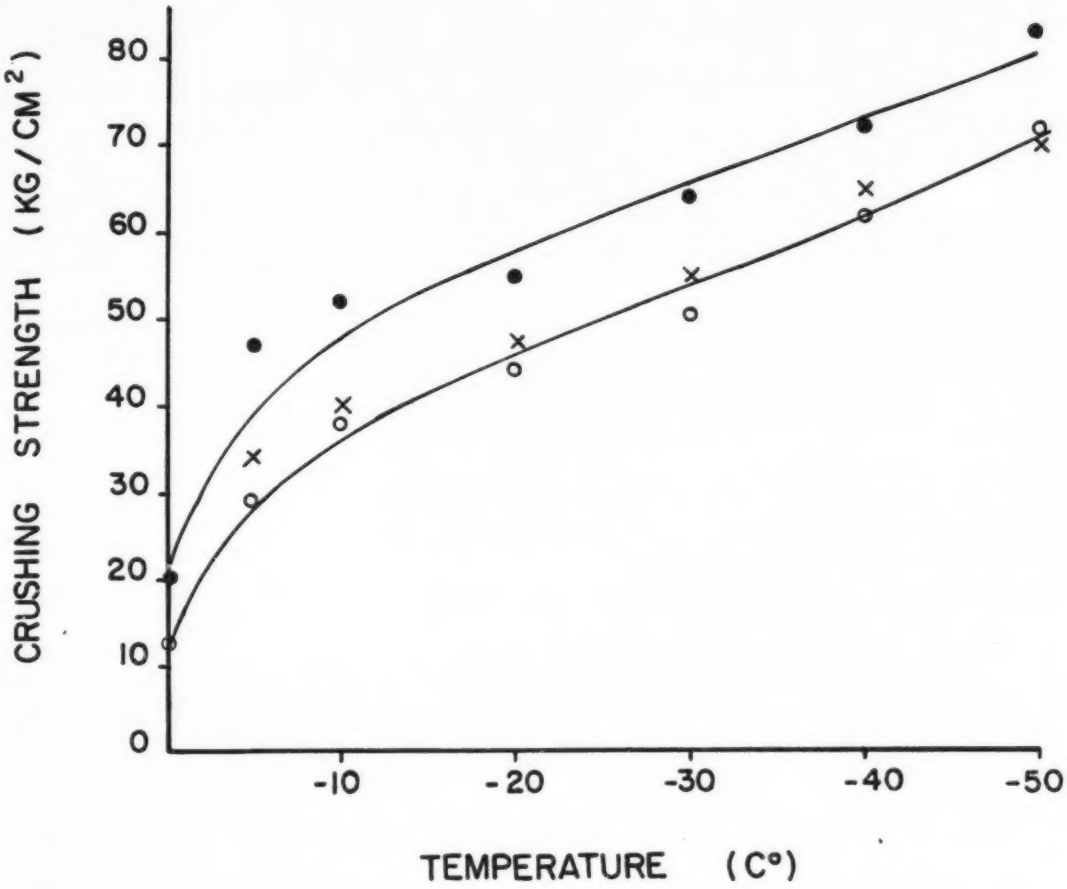


Figure 1. Crushing strength of ice vs. temperature. From Butkovich, 1954

x - Commercial ice
● - Lake ice (parallel to growth direction)
o - Lake ice (normal to growth direction)

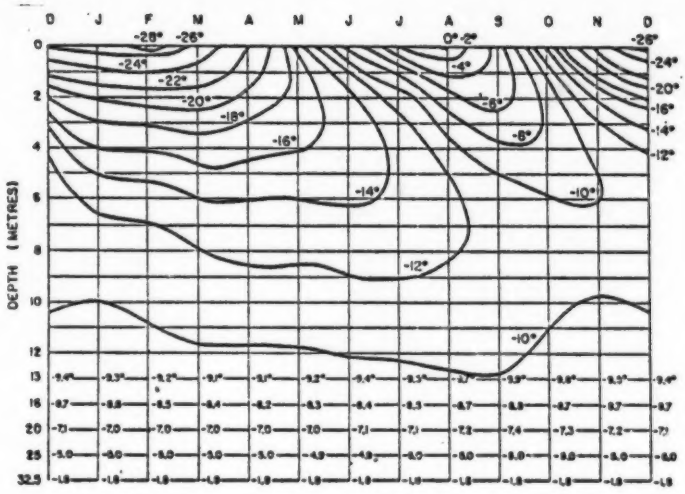


Figure 2. Vertical distribution of the ice temperature and its variations throughout the annual cycle. Ice Island "NP-19".

2.0 THE DATA BASE

The temperature of a berg depends primarily on three factors: 1) its original temperature at the time it calved from its parent glacier, 2) the temperature of the water it has been in and 3) how long it has been at sea.

2.1 Iceberg Temperature Data

Very few direct measurements of iceberg internal temperatures exist. Legenkov et al. (1974) studied the thermal regime of an ice island during one year and found a 10 m temperature of -10°C for this 32.5 m thick ice island (Fig. 2). Temple and Hill (1973) in the course of work in the Canadian archipelago in April, measured the temperature of a berg frozen into the sea ice at a depth of about 2 m from the surface. They obtained a reading of -22°C which suggests a 10 m temperature of roughly -17°C. Work on Antarctic icebergs which have been more thoroughly studied than those in northern waters has resulted in 10 m readings very close to -17° (Orheim, 1980).

2.2 Temperature Data from Ice Shelves, Ice Sheets and Glaciers

There are few data available on original iceberg temperatures in the northern hemisphere. Ten metre isotherms for the Greenland ice sheet have been calculated from temperature readings taken on transects of the sheet and from the latitude and elevations (Figure 3) but these calculated isotherms approach the sea in only one small area of the island, in the vicinity of Camp Tuto and Camp Century near Thule (Figure 4) where the U.S. Army

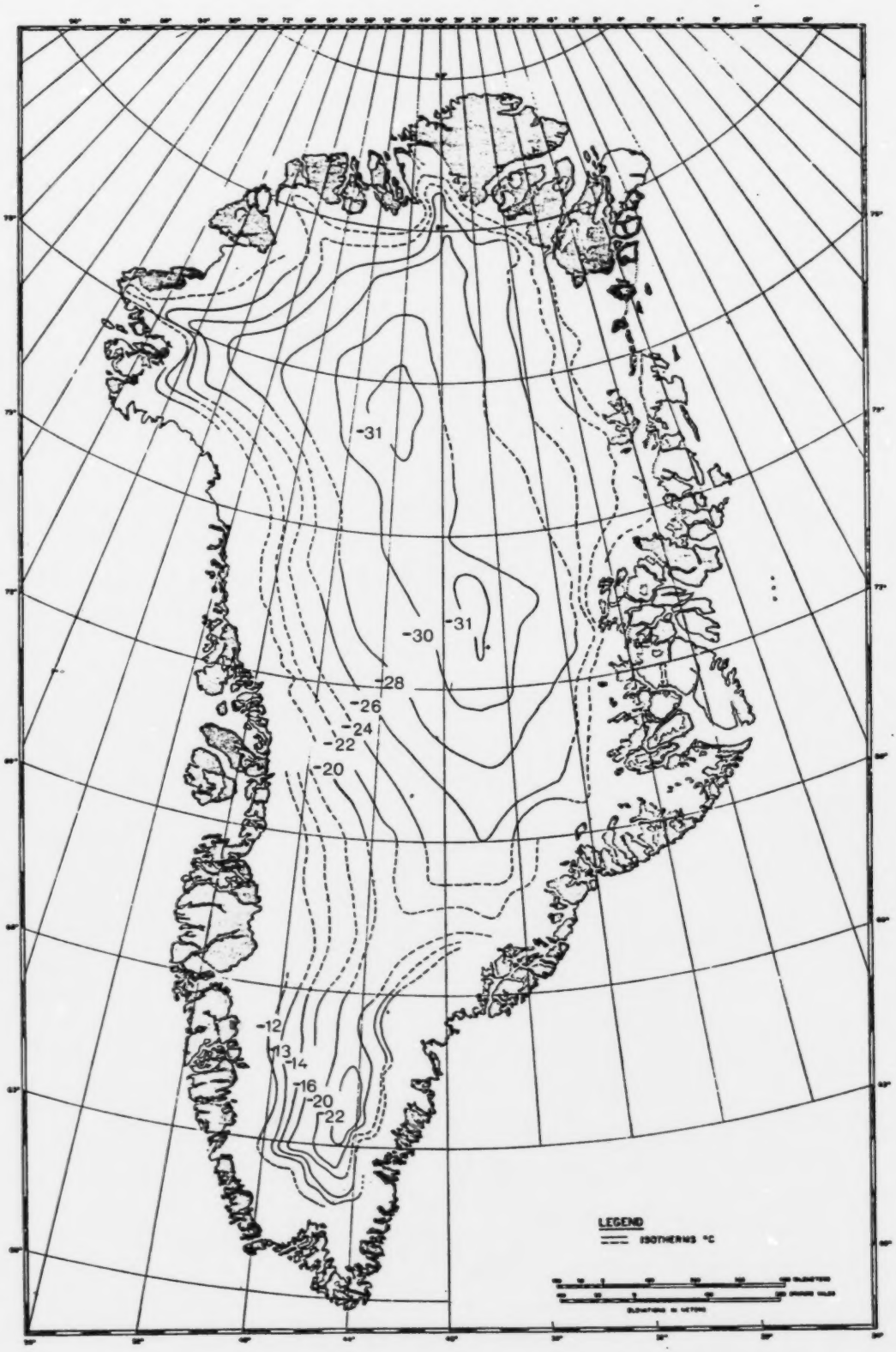


Figure 3. Isotherm contour map of Greenland showing 10-metre temperatures. (From Mock & Weeks, 1965).

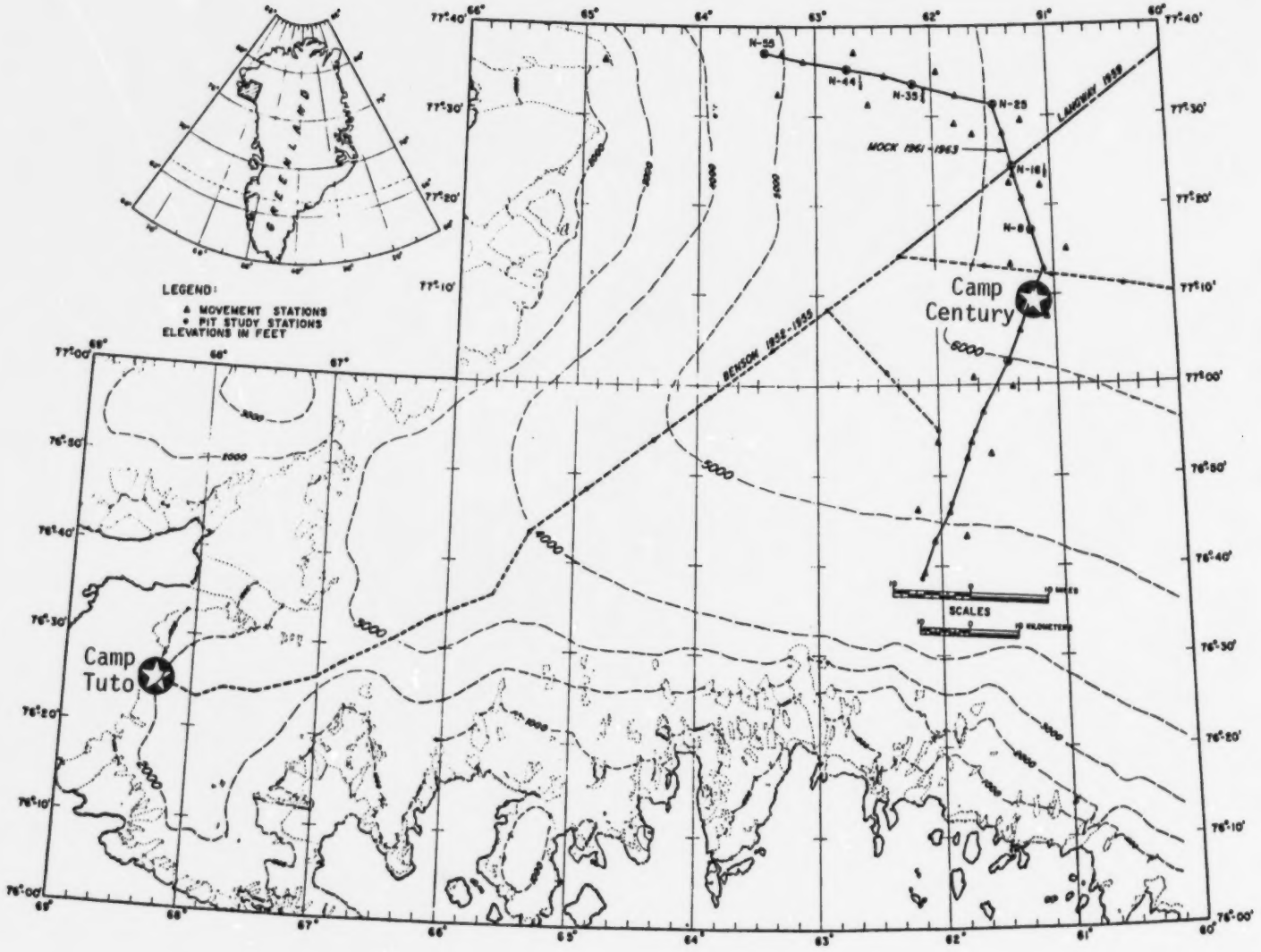


Figure 4. Location map showing Camp Century and Camp Tuto.

has done extensive work on ice properties. In a 1400 m borehole drilled by them at Camp Century, about 100 km from the sea, the temperature varied from a minimum of -24°C at 150 m depth to -13°C at the bottom (Hansen and Langway, 1966; Weertman, 1968). Another glacier thermal profile in northern Canada, on Axel Heiberg Island, suggests somewhat warmer ice than this with a range of temperatures near the terminus of from -12° to -3° (Muller, 1976). This is not a major outlet glacier nor is it in the area of heavy berg production. The reason for its relative warmth is unclear.

Ten metre ice sheet temperatures on Antarctica as shown in Figure 5 are very similar to those in Greenland at the corresponding latitudes and elevations. The huge ice shelves responsible for the production of most of the large tabular bergs in the southern oceans have been studied extensively. The 10 m temperatures on the Ross Shelf range from about -23° to -28°C (Thomas, 1976). Along the Budd Coast the bulk temperature measured at an elevation of 1166 m was -19.5°C while at 262 m elevation it was -7.7°C (Cameron, 1964). This situation very nearly parallels that at Camp Century and Camp Tuto where the equivalent temperatures were 5° colder.

These data suggest that an original temperature range of bulk temperatures between -15°C and -20°C might reasonably be expected for icebergs in the Labrador Sea.

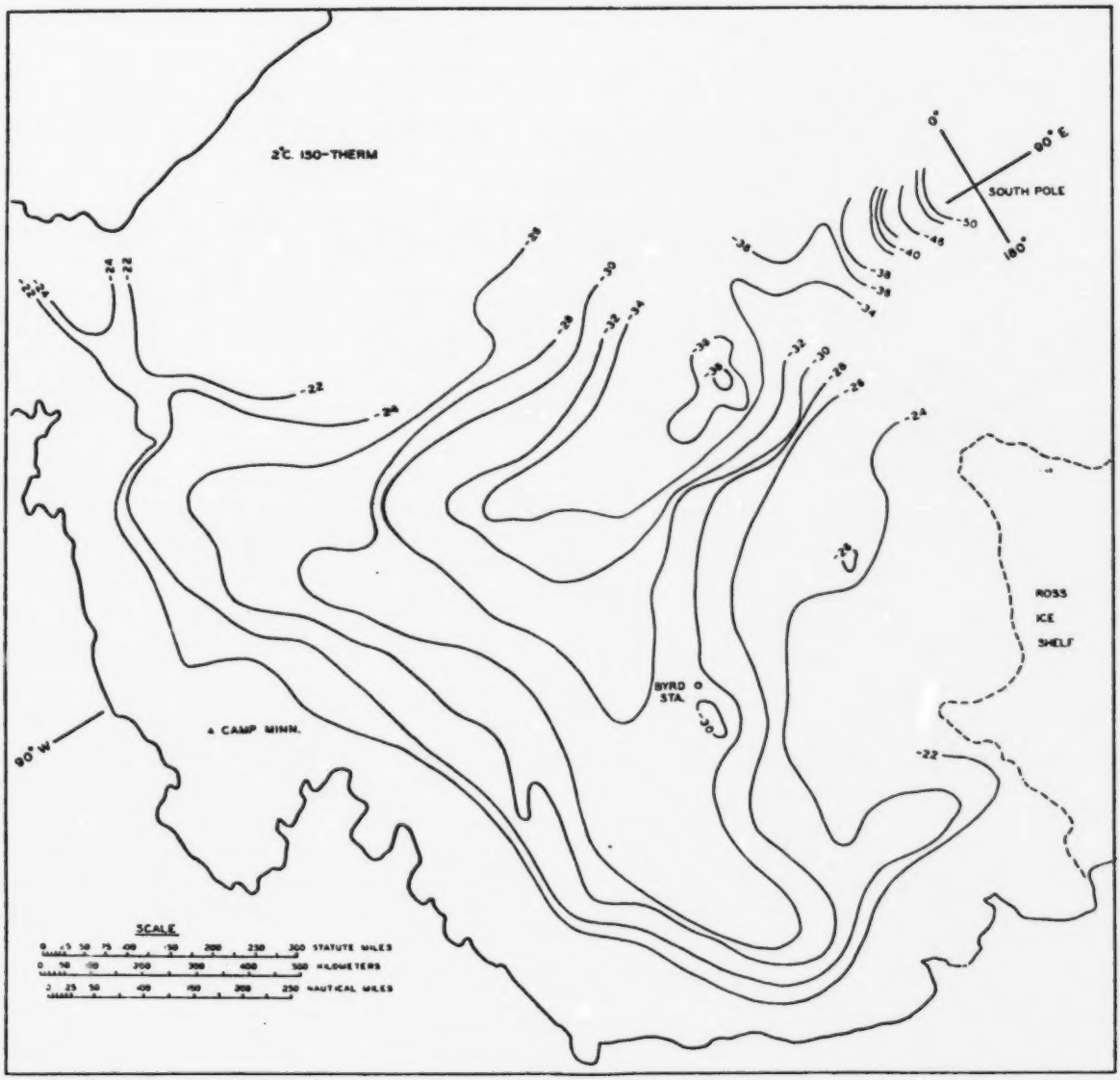


Figure 5. Isotherm contour map of West Antarctica showing 10-meter snow temperature. (From Mellor, 1964)

2.3 Iceberg Origins and Trajectories

The remaining two factors governing the temperatures of the Labrador icebergs, namely water temperature and residence time, are best considered together. It is commonly thought that most of the icebergs reaching Labrador originated on Greenland glaciers north of the Davis Strait Ridge, with minor contributions from eastern Greenland and Canadian sources (Kollmeyer, 1980, Robe 1980). After calving, it is thought that most of the icebergs then move around Baffin Bay in an anti-clockwise direction, remaining in the bay and its associated fjords for several years or more before passing southward through Davis Strait and down the Labrador Coast (Figure 6). Water temperatures in Baffin Bay are seldom reported as higher than 2°C, and then only in relatively small, stagnant bays and fjords for short periods of time during the summer (Smith, Soule, and Mosby, 1937, US Coast Guard, 1969, Codispoti and Kravitz, 1967). In general, water temperatures in this region are 1°C or less as the warm Atlantic water impinging on south-western Greenland extends no further north than the Davis Strait Ridge. Thus the bergs should experience no appreciable ablation until they pass Hudson Strait on their trip south.

Figure 6. Drift paths of icebergs found off Newfoundland and Labrador

3.0 ANALYSIS OF LINEAR HEAT FLOW IN AN ABLATING ICEBERG

Theoretical and laboratory studies (eg. Clifford et al., 1980) suggest that the bulk temperature of an iceberg should remain unchanged in sea water at 2° or greater. Above this temperature ablation would act in opposition to the very low thermal conductivity of the ice, tending to cancel any warming effect. Thus the thermal gradient from the ice/water interface to the centre of the ice will be very steep at all times. At temperatures below 1°C, however, where ablation is minimal the interior will gradually warm resulting in the somewhat anomalous situation of bergs in cold water appearing warmer than those in warm water. The depth of thermal disturbance and slope of the gradient will depend on the length of time the berg has spent in the cold water. Thus, as the bergs drift south out of Baffin Bay and are exposed to the warmer surface waters in the Labrador Sea, ablation will increase and the warm outer layers will be reduced such that the more southern bergs will possess a very steep thermal gradient from surface to core temperature. This process is represented diagrammatically in Figure 7.

The linear heat flow into a mass of ice at an initial uniform temperature may be demonstrated using Schmidt's graphical method as described in Ede (1967). The method provides a simple means of demonstrating the effects of ablation on the thermal gradients which develop in an ice mass in water at various temperatures. It relies on an averaging technique as follows: the initial temperature profile, density (ρ), thermal conductivity (k), and specific heat (c) are given. A convenient depth

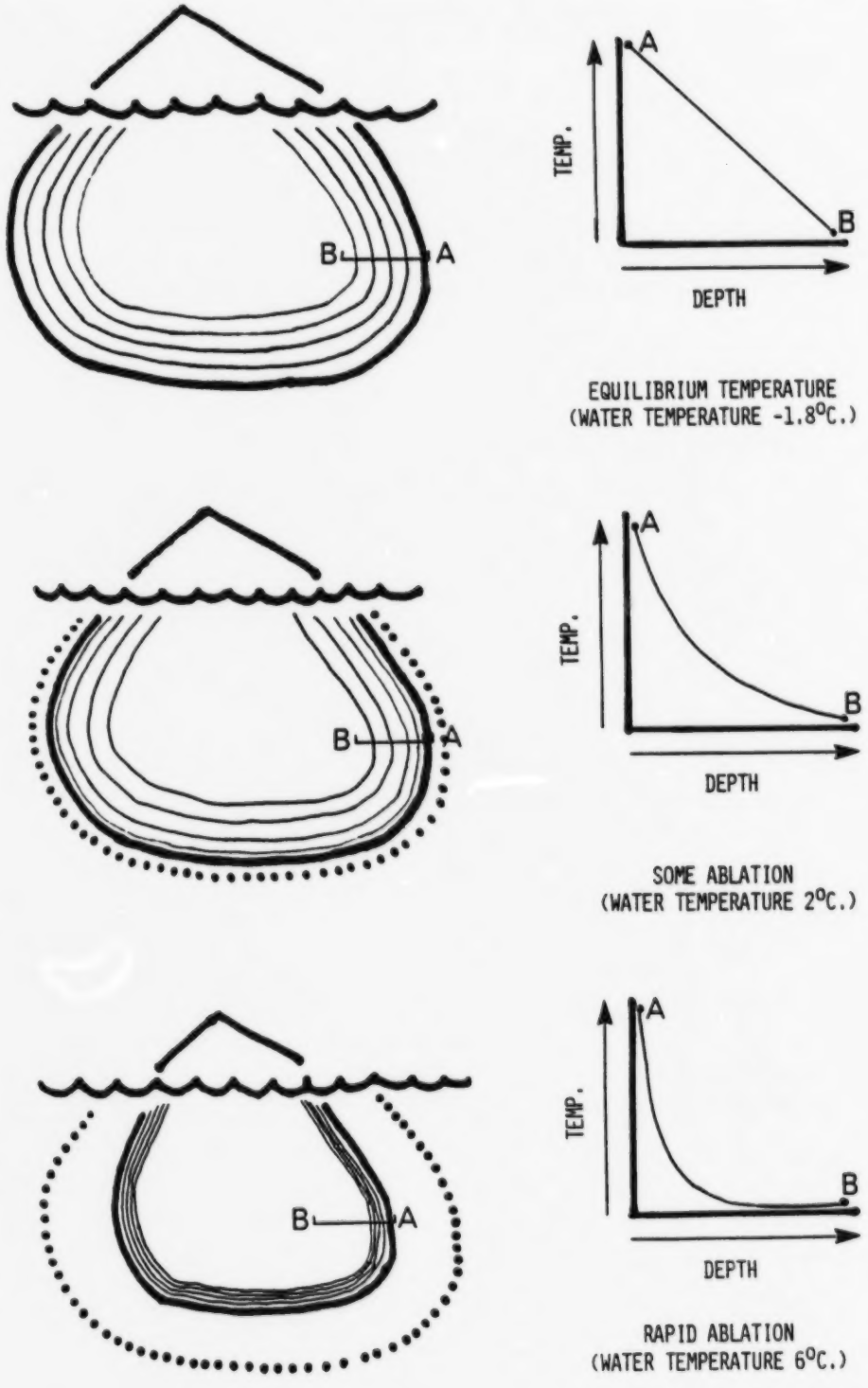


FIGURE 7. DEVELOPMENT OF A THERMAL GRADIENT IN AN ICEBERG. GRAPHS ACCOMPANYING SKETCHES SHOW THE CHANGE IN THE NATURE OF THE GRADIENT WITH INCREASING ABLATION. A = SURFACE TEMPERATURE; B = CORE TEMPERATURE.

•••• ORIGINAL CONTOUR

—— ISOTHERMS

increment into the ice (a) is chosen over which to examine the heat flow and a graph is drawn similar to figure 8. A temperature difference of $(T_A - T_B)$ is applied across slab AB and $(T_B - T_C)$ across BC yielding a net effect at B of

$$K\left(\frac{T_A-T_B}{a}\right) - K\left(\frac{T_B-T_C}{a}\right) = K\left(\frac{T_A+T_C-2T_B}{a}\right) \qquad (1)$$

The resulting change of temperature in a time increment, Δt, is

$$\frac{K(T_A+T_C-2T_B)\Delta t}{a} \div a\rho c = \frac{K}{a^2\rho c} \cdot \Delta t(T_A T_C 2T_B) \qquad (2)$$

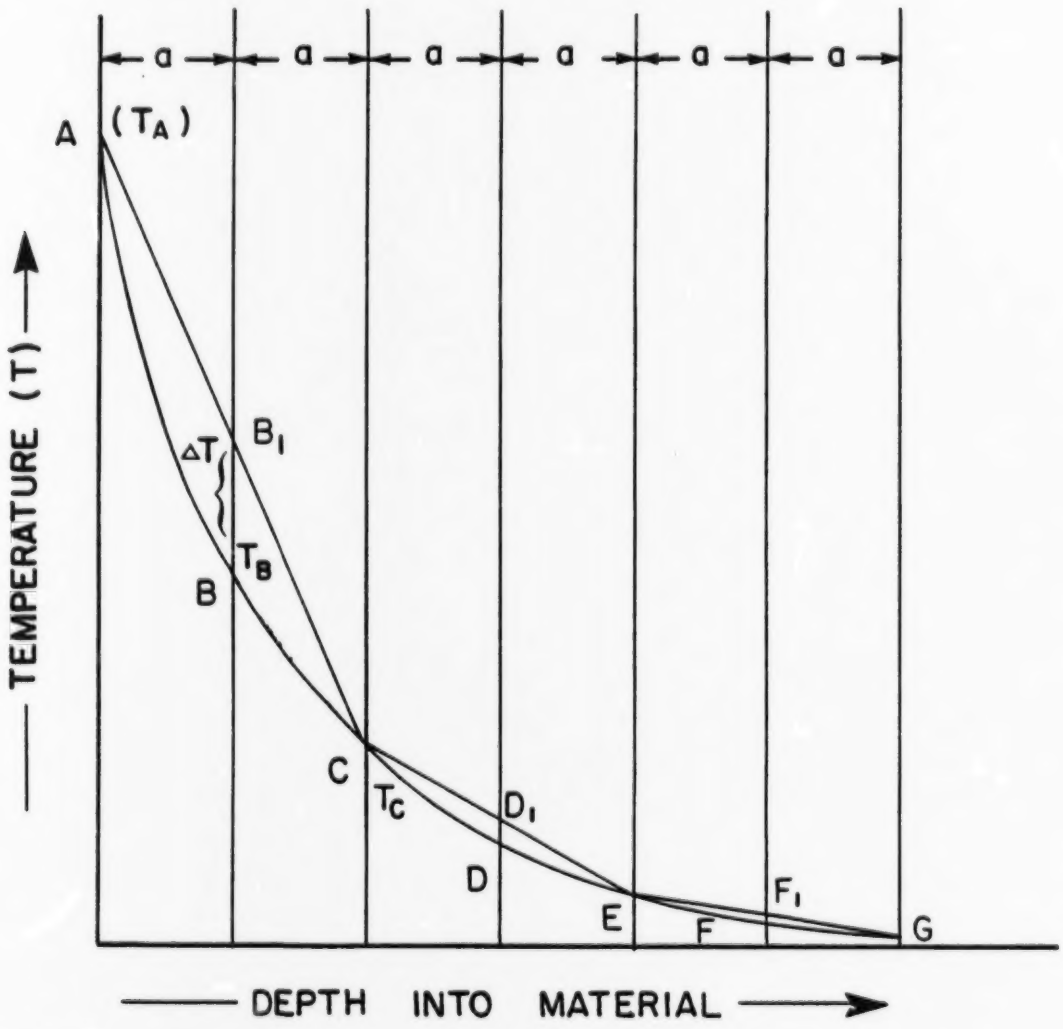


Figure 8. Schmidt's graphical method for heat flow from Ede,1967

If the time period is chosen such that

$$\Delta t = \frac{\rho c a^2}{2K} \qquad (3)$$

the temperature rise will be

$$\Delta T = \frac{T_A + T_C}{2} - T_B \qquad (4)$$

Thus $(T_A + T_C)/2$ defines B_1 and the temperature $(T_{B1} - T_B)$ is ΔT for the time period defined in equation (3). Iterating this procedure for slab CE, EG, etc. results in the definition of a new curve, B_1, D_1, F_1 ... which reflects the new thermal profile after ΔT. Repeating the process on this new curve results in the profile after $2(\Delta T)$ from the beginning and so forth for as many curves as are necessary to reach a solution for the final time period desired.

Values for density, specific heat and thermal conductivity as they appear in the literature and in standard reference books vary somewhat as can be seen in Table 1. In Figures 10 and 11 the following values are assumed:

ρ = 900 kg/M^3

k = 2.74 W/M ^oC

c = 1930 J/kg ^oC

a = 1 metre

From equation (3) ΔT = 4.49 days. Therefore, the final curves shown reflect the thermal profile after about 2 1/2 months.

TABLE I

	Thermal Conductivity W/m ^{o}C	Specific Heat J/Kg ^{o}C	Density Kg/m^{3}
Crary (1958)	2.22		
	2.25	2095	900
Clifford et al. (1980)	2.24		
Pounder (1965)		2100	860-917 [1]
Simonson (1967)	2.22	1926	913
Ede (1967)	2.2	2050	920
Cornwell (1977)	2.2	1930	913
Carslaw & Jaeger (1959)	2.22	2103	920
Landauer & Plumb (1956)	2.0		
Tennent (1971)	2.0	2100	920
Farouki (1982)	2.26(0^{o})-2.48(-30^{o})		
Powell (1958)	2.09 - 2.30		
Handbook Chemistry & Physics		2096(0^{o})-1866(-30^{o})	917(0^{o})
Cameron (1964)	2.74		870
Weeks & Mellor		2120	890
Langway (1958)			917 [2]
Fletcher (1970)	2.0 - 2.3	1900(-30^{o})-2020(0^{o})	
Orheim (1980)			715 - 882 [3]
Paterson (1969)			850 - 910 [4]
			400 - 850 [5]

[1] - pure ice
[2] - high density glacier ice
[3] - antarctic bergs
[4] - glacier ice
[5] - firn - at 830 bubbles are sealed off

Morgan and Budd (1977) working from data on size distribution and flux of Antarctic icebergs and average ocean temperatures in the area. calculated melt rates as shown in figure 9. Neshyba and Josberger (1980) have calculated theoretical melt rates for icebergs based on laboratory work, field observations, iceberg distribution statistics and theoretical studies. Their work suggests melt rates of 5, 17 and 55 m/yr for bergs in water at a temperature elevation above freezing point of 2, 4 and 8°C. These estimates are considerably lower than those of Morgan and Budd. These temperatures in seawater of salinity about 30 o/oo would be about 0°, 2° and 6°C. Relaxation curves presented here are based on these figures and do not take into account calving or temperature effects above the water line.

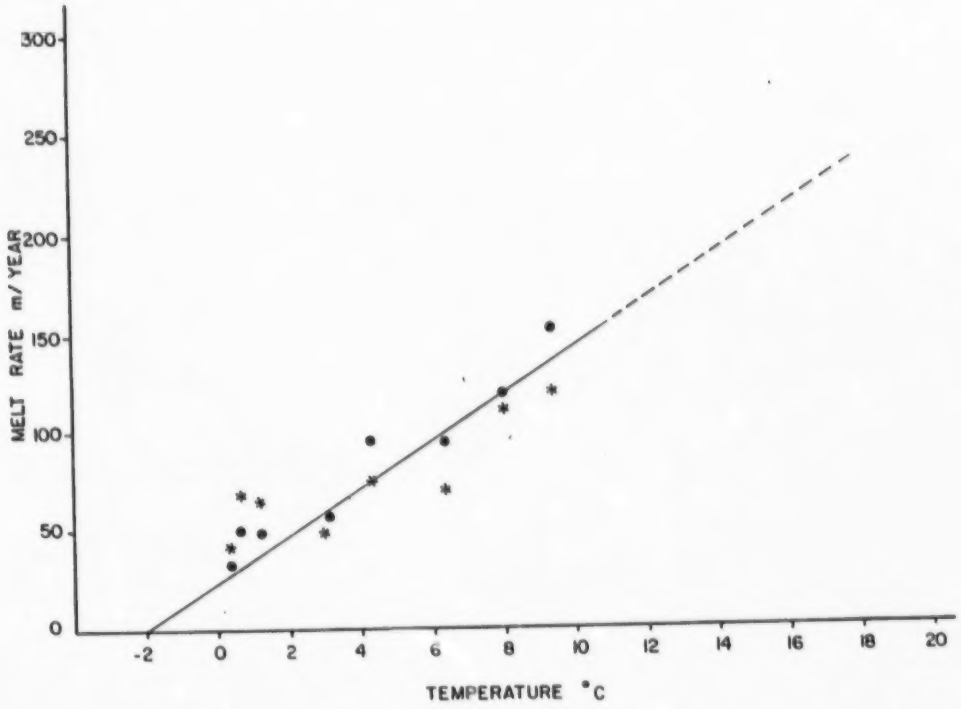


Figure 9. Average melt rates for the base (●) and sides (✱) of icebergs drifting north, shown as a function of mean water temperature (From Morgan & Budd, 1977)

Figures 10 a - e represent thermal gradients developed in a mass of ice with an initial uniform temperature of -20°C and physical parameters as defined above. The only variable is the ablation rate. As expected, for higher ablation rates, the thermal gradient becomes steeper and the depth at which the temperature is unchanged is nearer to the surface. It can also be seen that a stable thermal profile is developed very rapidly at higher ablation rates, about 1 month at 50 m/year.

Figures 11 a - e represent the thermal profiles expected in an ablating ice mass whose initial profile is the final curve in Figure 10a, i.e. the result of 2 1/2 months in water at the freezing point. It is clear that at the higher ablation rates the steady state thermal gradient is quickly developed. In the case of th 50 m/year ablation rate, as little as 9 increments (about 1 month) is sufficient.

Figure 12 gives a long-term view of the thermal profile. The total time period covered is about 4 years which is not an unreasonable time for an iceberg to have spent in the cold waters of Baffin Bay. At a depth of 50 m the original temperature is virtually undisturbed.

Figure 10. Thermal profiles developed in an infinite ice mass of uniform initial temperature (-20 C) in water at various temperatures resulting in ablation rates from 0 to 50 m/yr. Each curve on the individual graphs represents the thermal gradient developed after 4.49 days starting from the previous curve. The final curve depicts the thermal profile after 81 days.

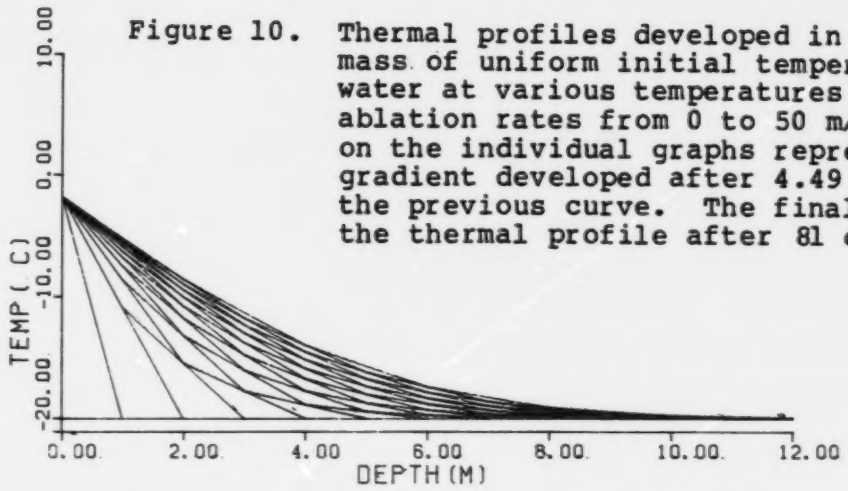


Figure 10a. ABLATION RATE (M/YR) 0.0

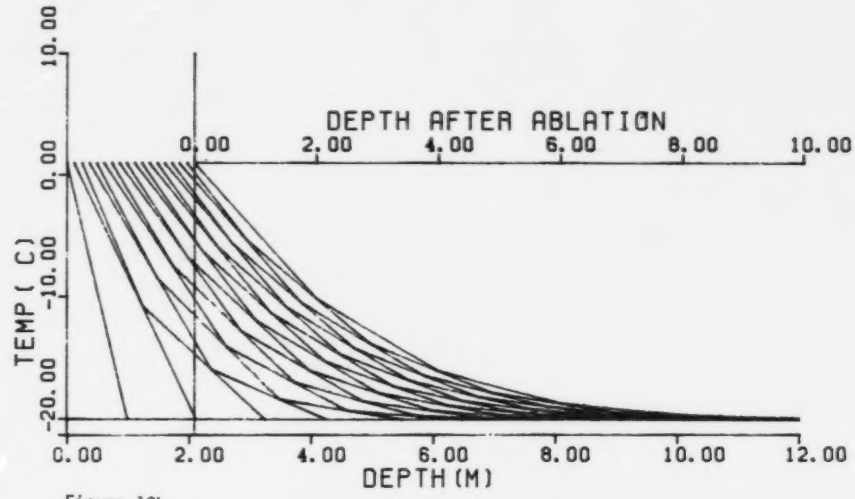


Figure 10b. ABLATION RATE (M/YR) 10.0

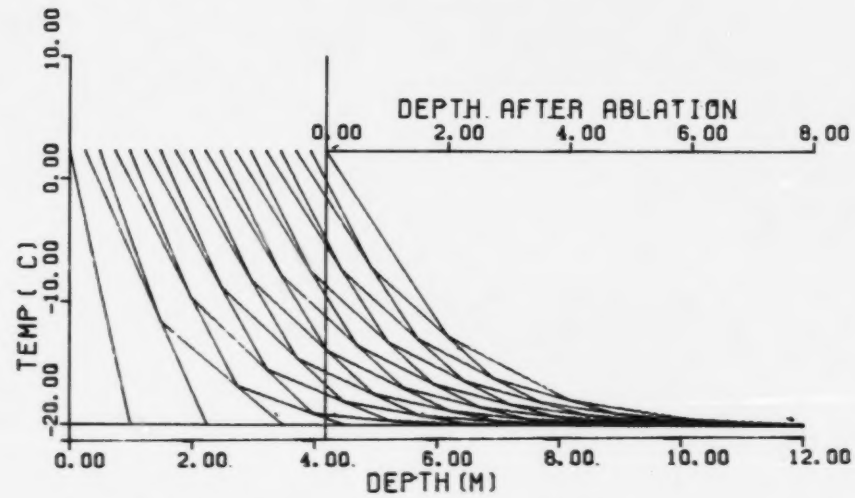


Figure 10c. ABLATION RATE (M/YR) 20.0

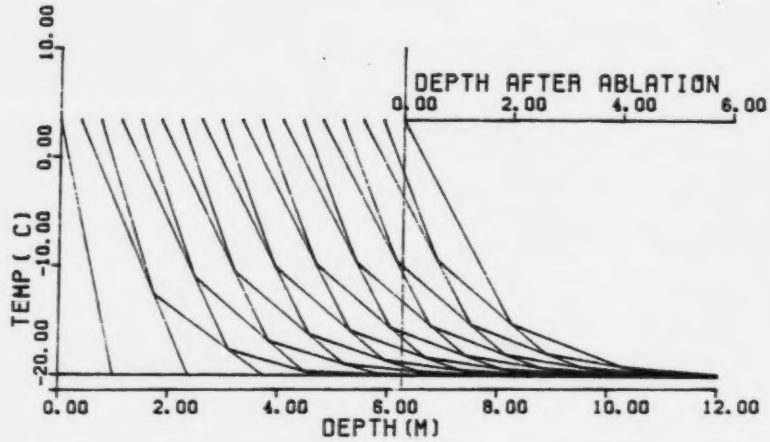


Figure 10d. ABLATION RATE (M/YR) 30.0

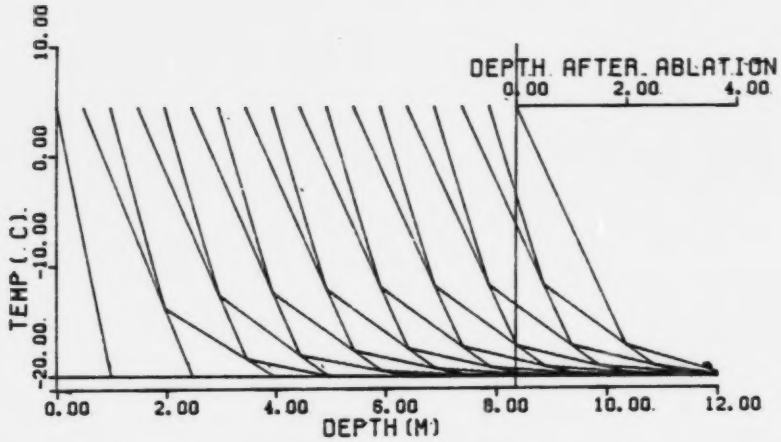


Figure 10e. ABLATION RATE (M/YR) 40.0

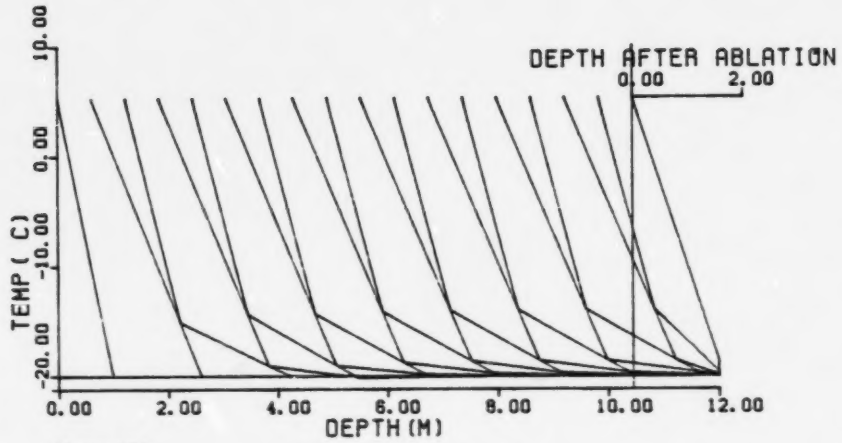


Figure 10f. ABLATION RATE (M/YR) 50.0

Figure 11. Thermal profiles of an ablating ice mass with an initial thermal gradient in place as represented by the final curve in Figure 10a.

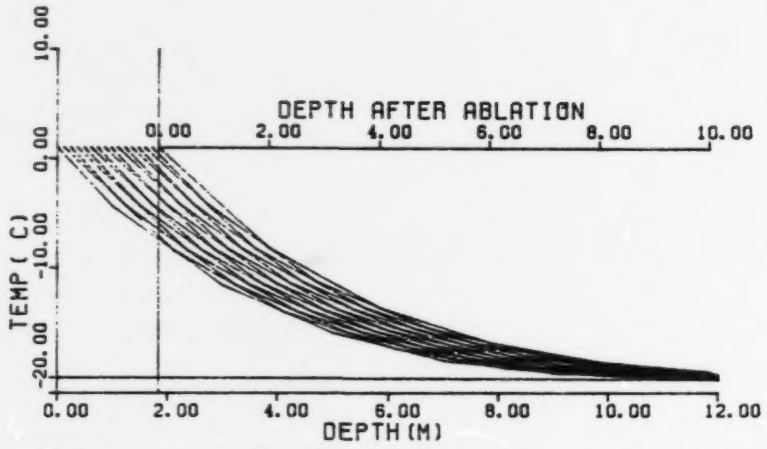


Figure 11a. ABLATION RATE (M/YR) 10.0

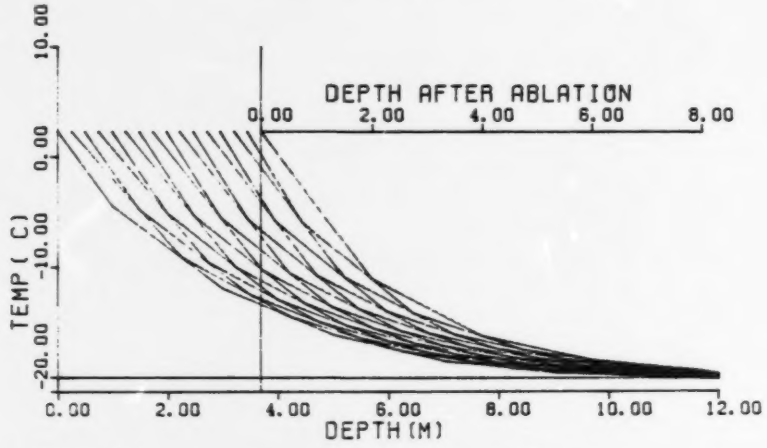


Figure 11b. ABLATION RATE (M/YR) 20.0

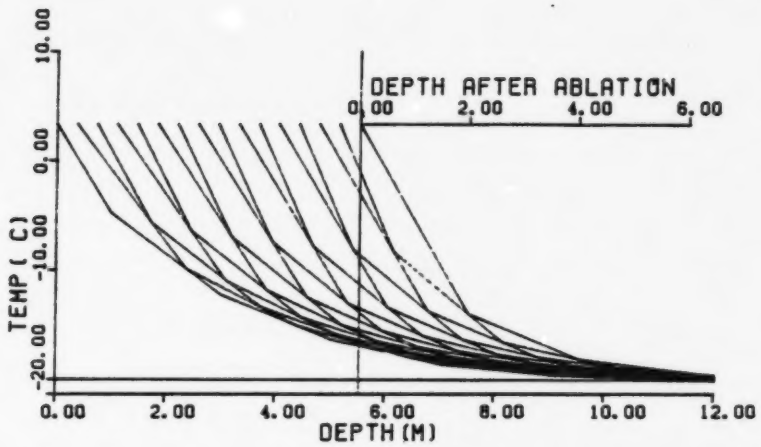


Figure 11c. ABLATION RATE (M/YR) 30.0

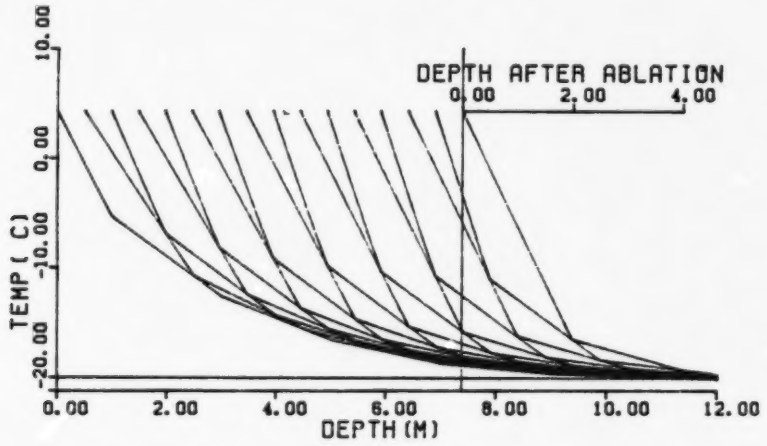


Figure 11d. ABLATION RATE (M/YR) 40.0

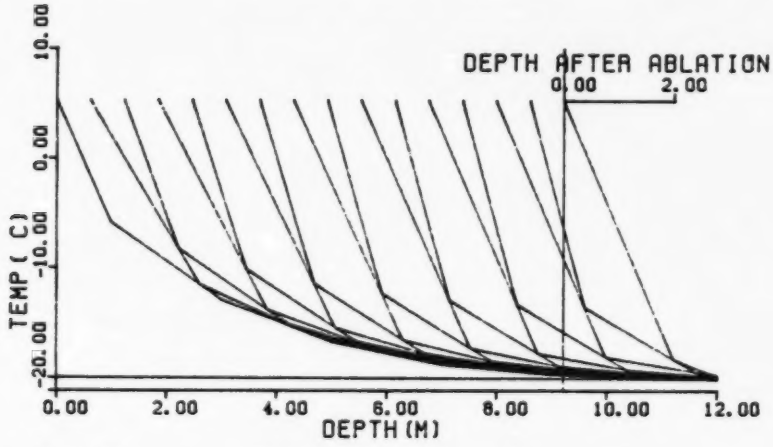


Figure 11e. ABLATION RATE (M/YR) 50.0

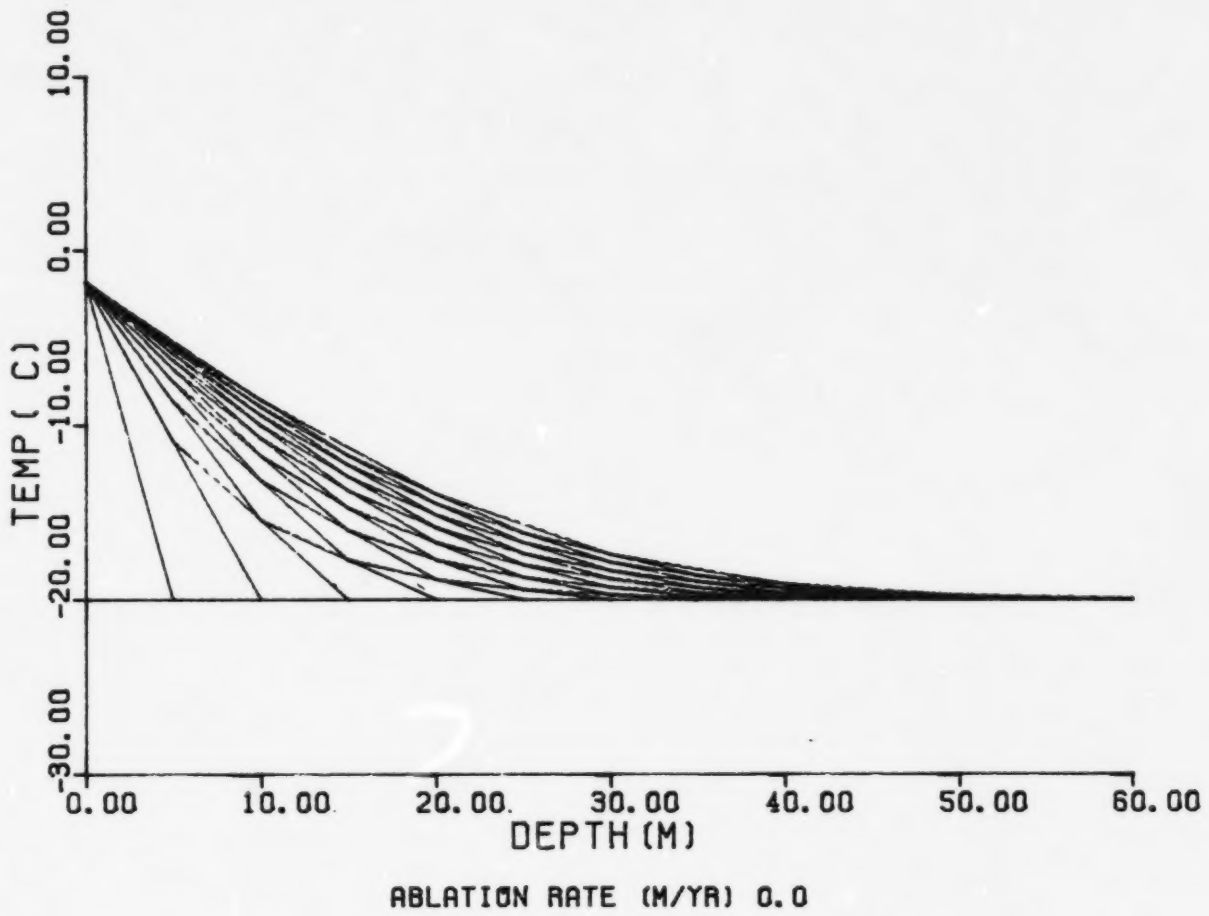


Figure 12. Thermal profile developed in a mass of ice suspended in seawater at -1.8 C. The final curve represents the thermal gradient after four years.

4.0 EXPERIMENTAL WORK

It is commonly thought that icebergs off southern Labrador and on the Grand Banks will be at or near 0°C. However, from the above discussion there is good reason to expect that an iceberg in this region will be no less cold or hard than one freshly calved in Baffin Bay. Preliminary data appear to confirm this hypothesis.

To date temperature measurements have been taken of three icebergs using a Precision Radiation Thermometer (Barnes Engineering, Model: PRT-5). This device is a remote radiation thermometer which detects naturally emitted radiation from targets which fill its field of view. The optical unit compares the energy emitted by the target with that emitted by its internal reference cavity through use of a thermistor bolometer. A spectral filter limits measurement to wavelengths between 8μ and 14μ . This window is used because it lies between the high infrared absorption region of CO_2 (around 15μ) and water vapor (around 6.3μ). This allows for its effective use from a considerable distance, such as in an aircraft. Its field of view is 2.5 milliradians (0.14°).

The first iceberg measured was a small berg grounded outside Petty Harbour, Newfoundland, in mid-June. It gave readings ranging from -5°C to -8.5°C with one perhaps anomalous reading of -11°C.

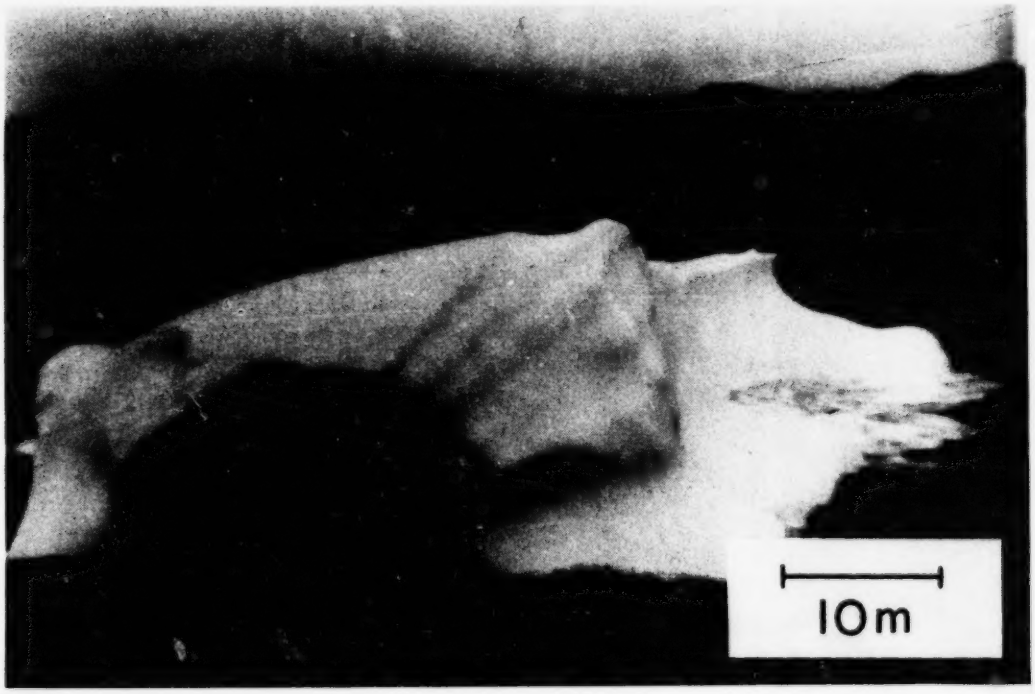
The other 2 icebergs were located on Hamilton Bank at about 54° to 55°N. The first of these was relatively warm with an average temperature of about -3° and a low of -4.5°C. The other

was somewhat colder with a low of -7°.

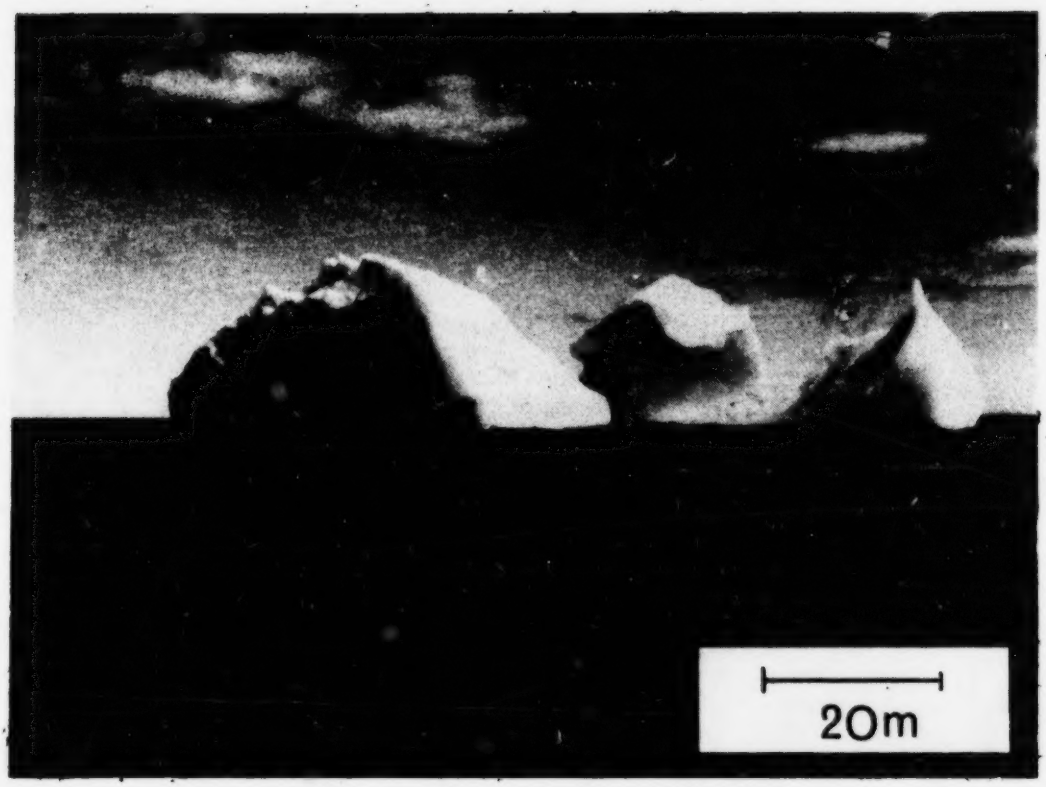
Photographs of these bergs are shown in Figure 13 a - c; the scale indicating size is approximate.

All of these bergs were roughly the same size, perhaps in the order of 1,000,000 tons, and all showed low readings at the waterline. Considerable variation in surface temperature was largely independent of sunny and shaded areas. The PRT-5 readings obtained appear surprisingly low at first inasmuch as the ambient air temperature was well above freezing, about 15°C, and thus the berg should have been covered in a film of melt water. This

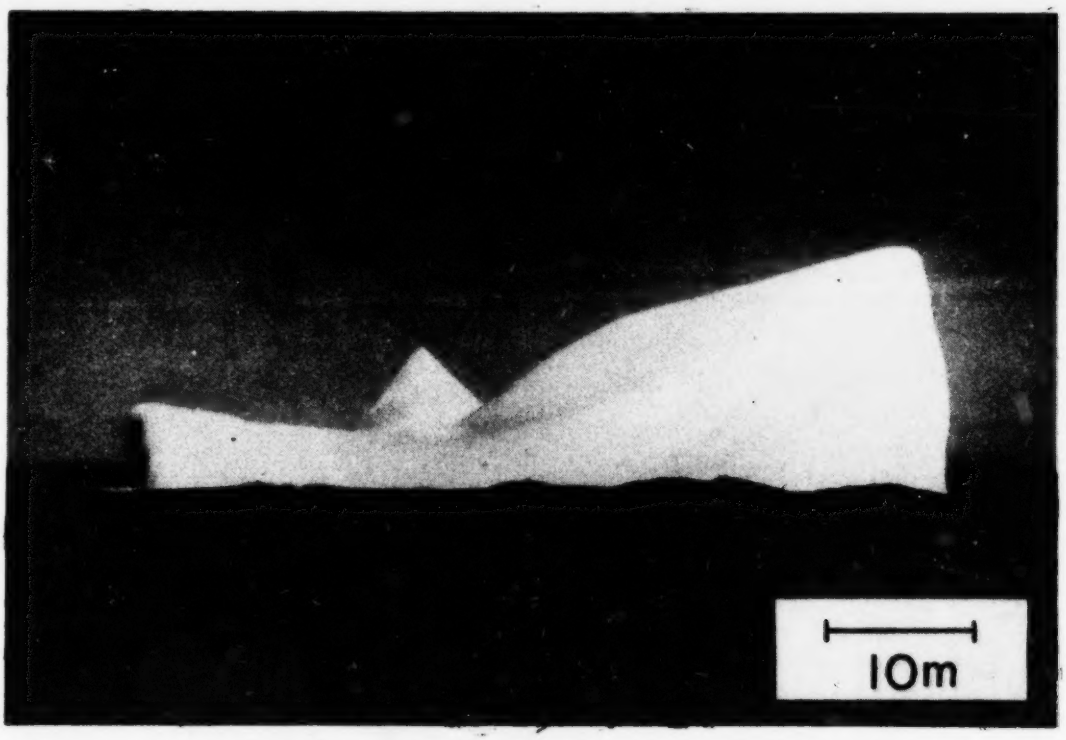
Figure 13a - 13c. Icebergs measured summer 1982



13a. Near Petty Harbour, Newfoundland



13b. Hamilton Bank, Labrador



13c. Hamilton Bank, Labrador

should have resulted in readings at or close to 0°C, since the PRT-5 would be detecting the infrared emissions from the surface meltwater rather than the colder ice beneath.

A simple explanation of this phenomenon is that if the ice was at the temperature indicated, i.e. several degrees below freezing point, a film of meltwater could not exist. Since the albedo of iceberg ice is so high, heating from the sun would have little effect. In this connection, it is interesting to note that the clear blue cracks melt more rapidly than the surrounding bubbly ice. Temperature readings from these cracks were ambiguous.

Other investigators have obtained similar results: Foldvik, et al. (1980) on an Antarctic tabular berg in midsummer and Muller et al., (1975) on an iceberg trapped in sea ice near Jones Sound in March. A PRT-5 was used in both of these studies. Both of these icebergs were measured from aircraft. The Jones Sound iceberg was frozen into the surrounding pack ice and measured about 4° colder than the sea ice. The Antarctic iceberg was surrounded by seawater at 0° or less while the berg itself measured -6° uniformly across two transects. Another iceberg measured by Foldvik, et al. gave warmer temperature readings. The temperature of the surrounding water was the same in both cases while the redings from the warmer iceberg were very close to 0°, about 0.5° warmer than the surrounding water. These observations suggest that the readings given by the PRT-5 are a reliable reflection of the surface temperature of the ice.

Since the theory outlined above predicts that icebergs in

warmer water will have colder surface temperatures it is not surprising that the Petty Harbour iceberg gave readings of -8° in several places including the waterline. This berg showed evidence of considerable ablation and rolling (see Figure 12a). Readings were taken on it both from a helicopter at about 50 to 100 meters distance as well as from a fishing vessel at about 15 meters distance. Of the two icebergs on Hamilton Bank visited in late August by boat, one (Figure 13b) yielded waterline temperatures ranging from -3°C to -5°C with values at higher levels of -1° to -4.5°. The other (Figure 12c) gave lower readings, at the waterline and on the sail, with a minimum reading of -7° on one side. The fact that neither of these icebergs gave readings as cold as the Petty Harbor iceberg supports the ideas discussed above.

5.0 SUMMARY

The bulk of the evidence suggests that original temperatures of icebergs found in the Labrador Sea should be in the vicinity of -17°C. Theoretical considerations indicate that the bulk temperatures should remain unchanged from their original values even after prolonged residence in seawater. In fact, as the iceberg moves out of Baffin Bay and into the warmer waters off Labrador and Newfoundland the accelerated ablation will diminish any warmer outer layers which have developed during residence in the cold northern waters. This would result in an iceberg whose cold core will be very close to the surface.

This is of considerable practical significance to those involved in the design and installation of non-mobile and semi-mobile structures since the strength of ice near its melting point is highly dependant on its temperature.

Further work is planned to test the hypothesis that the bulk temperature of icebergs in the Labrador Sea is virtually unchanged from that of their parent glaciers. It is hoped to make direct borehole measurements of recently calved icebergs as well as grounded bergs in Baffin Bay and along Labrador. In addition, measurements will be made of drifting icebergs using the PRT-5 as well as an instrumented projectile which is currently being developed. Emphasis will be placed on waterline readings as this is the area of greatest ablation. The cold interior ice being closest to the surface in this area should therefore have the steepest thermal gradient.

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